AD-A275 114

NTATION PAGE

Form Approved
OMB No. 0704-0188

RT DATE	3 REPORT TYPE AND DATES COVERED
December 1993	Professional Paper

4. TITLE AND SUBTITLE

LOW-THRESHOLD DYE LASER PUMPED BY VISIBLE LASER DIODES

5. FUNDING NUMBERS

PR: CH84
PE: 0601153N
WU: DN300190

6. AUTHOR(S)

R. Scheps

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

DTIC
ELECTE
JAN 14 1994
S E D

94-01577

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. ABSTRACT *(Maximum 200 words)*

This paper describes work with a low-threshold dye laser pumped by visible laser diodes. A continuous-wave (CW) dye laser has been pumped by laser diodes for the first time. Two 10-mW visible laser diodes were polarization-combined to pump a rhodamine 700 dye jet laser. The absorbed pump threshold power was 5.6 mW, and 0.28 mW of output power was produced at 758 nm. The resonator was scalable and generated over 360 mW with a slope efficiency of 57 percent when pumped with a DCM dye laser at 660 nm.

14. SUBJECT TERMS

dye laser
laser diodes

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

NSN 7540-01-280-5500

94 11 13 061

Standard form 298 (FRONT)

21a NAME OF RESPONSIBLE INDIVIDUAL	21b TELEPHONE *(include Area Code)*	21c OFFICE SYMBOL
R. Scheps	(619) 553–3730	Code 754

Low-Threshold Dye Laser Pumped by Visible Laser Diodes

Richard Scheps

Abstract—A continuous-wave (CW) dye laser has been pumped by laser diodes for the first time. Two 10-mW visible laser diodes were polarization-combined to pump a rhodamine 700 dye jet laser. The absorbed pump threshold power was 5.6 mW, and 0.28 mW of output power was produced at 758 nm. The resonator was scalable and generated over 360 mW with a slope efficiency of 57% when pumped with a DCM dye laser at 660 nm.

CONTINUOUS-WAVE (CW) dye lasers are versatile devices that are useful for a wide range of applications. However, the ion lasers typically used as pump sources are both expensive and inefficient. For dyes that absorb at 532 nm, the second harmonic of a diode-pumped Nd:YAG laser can provide the necessary pump intensity. This greatly enhances the overall efficiency. Unfortunately, dye lasers operating above 700 nm demonstrate poor optical conversion efficiency when pumped with visible wavelengths shorter than 600 nm. The recent introduction of moderate-power red laser diodes has provided the opportunity to demonstrate a diode-pumped dye laser emitting in the 700- to 800-nm wavelength range. These diodes have AlGaInP active layers and operate between 620 and 690 nm. The currently available CW diode power of 0.5 W is competitive with small krypton ion lasers.

The first demonstration of a diode-pumped dye laser was reported in 1974 [1]. A 50-ns pulsed AlGaAs laser diode operating at 820 nm was used to excite an IR 140 dye solution in a waveguide laser. Subsequently, rhodamine 6G and coumarin 47 dye lasers were demonstrated [2] using a 25-ns pulsed, e-beam excited, CdS or ZnO semiconductor laser, respectively. While these investigations are of interest, neither technology can be efficiently scaled to higher power. In the present work, the first demonstration of a CW, diode-pumped dye laser is reported. A rhodamine 700 dye jet in a hemispherical resonator was pumped using two 10-mW, commercially packaged visible laser diodes operating at 672 and 674 nm, respectively. The power source for the diodes was four AA batteries. An argon ion laser-pumped DCM dye laser was used to characterize the dye laser and determine the variation in operating parameters as a function of

pump power and wavelength. The laser design reported below is shown to be both practical and scalable.

A schematic of the laser resonator is illustrated in Fig. 1. The configuration is similar to that used for diode pumping Cr-doped solid state tunable lasers [3], [4]. The laser resonator consists of a highly reflective (HR) flat and a 10-cm radius-of-curvature output mirror in a nearly hemispherical resonator. The HR flat is a 2-mm-thick plane-parallel quartz plate with a dichroic coating on one face that is HR from 720 nm to 850 nm and highly transmissive (HT) from 650 nm to 680 nm. The plate was oriented so that this coated face was interior to the laser cavity. The exterior face of the flat (closest to the pump source) was uncoated. The output couplers were broadband-coated to reflect both the pump and laser emission wavelengths. The dye jet was 100 μm thick and placed as close to the HR flat as practical. The spacing between the jet and interior face of the flat was on the order of 400 μm.

Three different pump sources were available: two laser diodes and a CW DCM dye laser. The output of each laser is plane polarized. The pump geometry permits excitation of the rhodamine 700 dye by any combination of the three pump sources. This is accomplished with the use of two polarization beam combiner cubes (PBC) and a half-wave plate. The dye laser and one of the laser diodes (LD 1) have orthogonal polarizations, and both outputs are combined by the first PBC (PBC 1). The ratio of laser diode to dye laser power from PBC 1 that is transmitted through the second PBC (PBC 2) is determined by the orientation of the half-wave plate. In the absence of polarization rotation the dye laser power is completely reflected out of the pump path by PBC 2. Emission from the second laser diode (LD 2) is polarized parallel to the dye laser output and is folded into the pump path by reflection from PBC 2. The laser diodes emit a collimated output beam. Due to losses in the pump relay optics, the maximum laser diode power incident on the 14.5-mm focusing lens was 13.5 mW.

Considering the level of available laser diode power, it was important that the dye laser be designed to exceed threshold at low pump power. This required extremely low-loss HR coatings on the reflective optics and careful adjustment of the position of the dye jet and focusing lens. The dye concentration was optimized for pumping at 670 nm. Initially a concentration of 7.95×10^{-4} M was prepared. This dye density is similar to that reported [5]
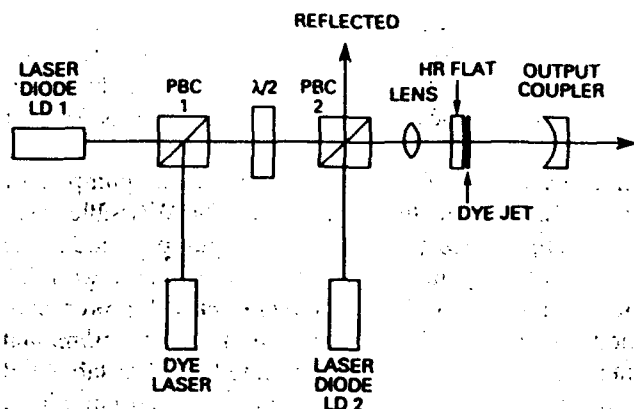
Fig. 1. Schematic of the pump and resonator geometry for the diode-pumped dye laser. The polarizing beam combining cubes are labeled PBC 1 and PBC 2, the laser diodes are labeled LD 1 and LD 2, and the half-wave plate is labeled $\lambda/2$. The view in the figure is a top view, and the jet is horizontal.
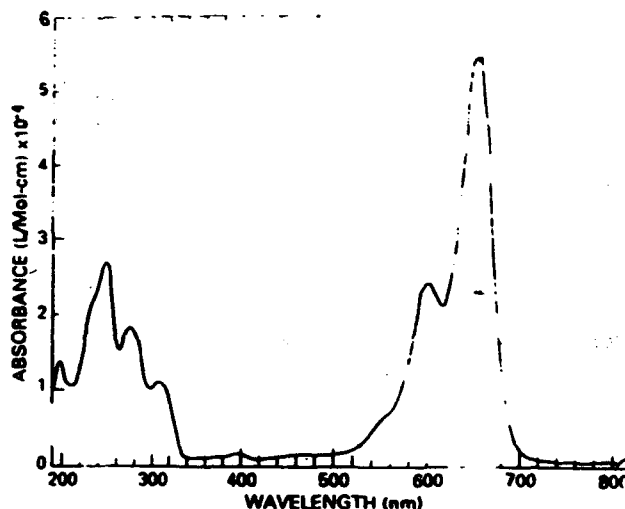

Fig. 2. Absorption spectrum of rhodamine 700 in ethylene glycol taken with a diode array spectrophotometer. The resolution is 2 nm, and the peak absorbance of 5.46×10^4 L/Mol-cm occurs at 652 nm.

for a low-threshold rhodamine 700 dye laser pumped at 647 nm. However, the absorbed fraction of 670-nm pump power was only 41%, and consequently the power required to exceed threshold was too high. To achieve a higher absorbed fraction, a concentration of 1.76×10^{-3} M was prepared. For this concentration approximately 70% of the pump power at 670 nm was absorbed in a single pass. The solvent in both cases was ethylene glycol, and the absorption spectrum of rhodamine 700 is shown in Fig. 2. To determine whether the dye temperature influences the laser threshold, the temperature of the dye solution was varied between 10 and 20 °C. Little effect on the laser operation was observed, and the measurements reported below are for a 12 °C dye solution.

There are several significant benefits of using the resonator illustrated in Fig. 1 when low-threshold operation is an important consideration. For one, longitudinal pumping allows the pump beam to be focused with a short-focal-length lens, resulting in a small pump waist at the dye jet. Pumping the jet at an angle to the resonator axis, as is done in many commercial CW dye lasers, would require a longer-focal-length lens since the lens diameter will interfere with the resonator mode if the lens working distance is too short. In addition, a nonnormal angle of incidence for the pump axis relative to the jet flow axis produces an elliptical pump spot and consequently reduced pump power density. An additional benefit of longitudinally pumping the hemispherical resonator is that the pump beam can be matched to the resonator mode. Therefore the unabsorbed pump power is reflected by the output mirror back to the jet, where it undergoes a second pass. Since the absorption coefficient of rhodamine 700 at 670 nm is only half the peak value at 652 nm, the double-pass absorption allows good pump efficiency at a lower dye concentration. Note that the resonator passive losses decrease with decreasing dye concentration.

The dye jet flow axis is oriented orthogonal to the laser resonator mode. This reduces the laser threshold power requirement compared to the more traditional Brewster

orientation, as both the pump power density and extraction efficiency increase as the pump and resonator mode areas decrease [6]. Note also that although the resonator mode is reflected at both of the air–jet interfaces, these reflections are mode matched and do not add to the resonator loss. A Findlay–Clay [7] analysis was performed on the resonator by measuring the variation of 670-nm pump threshold power with output coupler reflectivity. The output mirrors ranged from HR to 96% reflective (R). From the threshold data, the passive loss was measured to be 2.75×10^{-3} per pass. An alternate measure of the passive loss was obtained from the variation of the slope efficiency with output mirror reflectivity [8]. This produced a value of 2.0×10^{-3} per pass. These single-pass loss values are low enough to produce low threshold pump powers, although the linear loss in the 100 μm jet is over 20%/cm.

In discussing the results obtained with the dye laser, several terms are used that have the following specific meanings. The pump threshold and slope efficiency data are based on the pump power absorbed by the dye jet, while the optical conversion efficiency is a measure of the ratio of dye laser output power to pump power incident on the focusing lens. The latter efficiency can be improved by reducing the approximately 17% optical loss between the focusing lens and the dye jet. The lowest absorbed threshold power was 5.6 mW at 670 nm using an HR output coupler. The pump spot diameter was measured at the dye jet and was 36 μ. The absorbed pump power density at threshold is therefore approximately 550 W/cm^2. This is lower than that reported previously [5] and is due in part to the relatively straightforward alignment of the hemispherical resonator used in this work compared to the critical alignment associated with the concentric resonator demonstrated in [5]. Using the diodes as pumps, the untuned laser output peak occurred at 758 nm and the full width half maximum (FWHM) of the
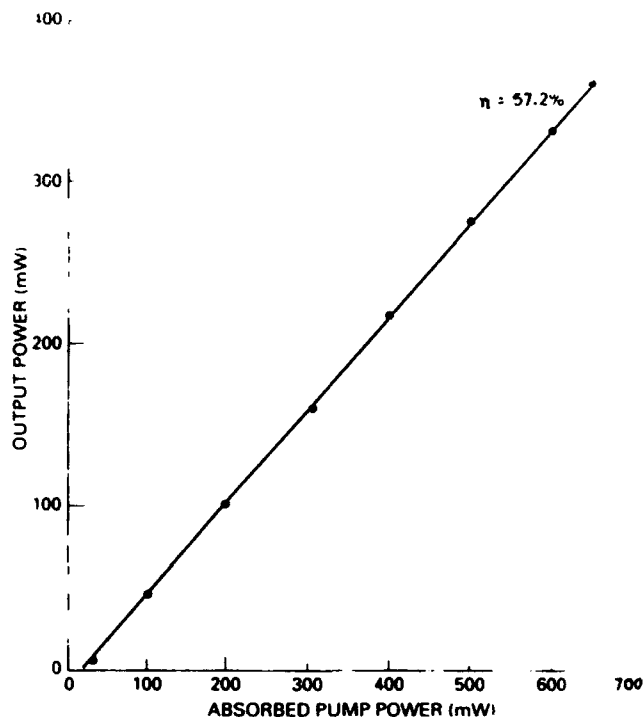
Fig. 3. Slope efficiency of the rhodamine 700 laser pumped at 660 nm with a DCM dye laser. The filled circles represent data, and the straight line is a linear regression fit to the data. The slope efficiency η is indicated.

output band was 16 nm. The maximum output power obtained was 0.28 mW, and the slope efficiency was 16%.

To determine the scalability of the resonator to higher output power a DCM dye laser pump was used in conjunction with several partial reflector output mirrors. With the pump wavelength fixed at 670 nm, the maximum output power obtained from the laser was 237 mW using a 0.967 R output mirror. The absorbed power was 571 mW, and the slope efficiency was 45%. A 0.985 R output mirror produced a slope efficiency of 39%. Using this mirror and pumping the dye at 660 nm, the slope efficiency increased to 57%, the optical conversion efficiency was 41%, and the output power was 361 mW at 742 nm. This slope efficiency is 64% of the quantum defect-limited slope. The observation of a pump wavelength dependence for the slope efficiency (which is based on absorbed power) is evidence of imperfect matching between the pump and

resonator modes. The power data are shown in Fig. 3. The highest efficiency for rhodamine 700 previously reported [9] was obtained with a single-frequency ring dye laser. The maximum optical conversion efficiency was 33% at 740 nm.

In conclusion, a CW dye laser has been pumped by laser diodes for the first time. Two 10-mW visible laser diodes were polarization-combined to pump a rhodamine 700 dye jet laser. The laser diodes were powered with AA batteries, and the only additional electrical power consumed was that required to operate the dye jet pump and chiller. The dye laser was demonstrated to be scalable and produced over 360 mW when pumped at 660 nm with a DCM dye laser. The bandwidth was 16 nm. Using currently available laser diode technology, 1 W of diode power can be obtained using polarization combination of two 0.5 W diodes. It is important to note that the unique properties of the dye jet (100 μm thick and high pump absorption) produce an essentially two-dimensional gain region. Scaling to higher diode pump power can therefore be accomplished in an efficient manner by angular multiplexing of multiple single-stripe laser emitters. This is in contrast to most solid-state lasers [3], where the pump must be spatially matched to the resonator mode over a distance of several mm.

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